IMPROVED FOCAL DEPTH DETERMINATION
FOR USE IN CTBT MONITORING

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ABSTRACT

Seismic event location remains as one of the most important discriminants for separating natural tectonic and explosive events. However, in order to be useful for discrimination purposes, the uncertainties associated with seismic locations must be well defined and reliable, and this has proven to be difficult to accomplish to the required degree of accuracy. In particular, high-confidence estimation of focal depths remains as an outstanding monitoring problem. During the past year, we have continued to pursue a research program which is directed toward the development of improved detection and identification procedures for the depth phases pP and sP, as well as with formulation of a new algorithm for computing more reliable confidence intervals on focal depth estimates determined from P-wave first arrival times. With regard to depth phase identification , we have continued to investigate the utility of the fully automatic network stacking algorithm which maps the IDC post-P detection times at a station into candidate depth phases using the pP - P and sP – P delay times predicted by the IASPEI travel-time tables for that epicentral distance and then combines the individual station results as a function of candidate source depth. This automatic algorithm has now been applied to data from about 150 REB events in the Hindu Kush and in the Hokkaido and central Honshu regions of Japan. Prominent candidate pP and sP peaks have been identified in the resulting network detections stacks for a majority of these events, including some with m_b values as low as 3.7 and depths as shallow as 50km. Current effort on this phase of the project centers on the incorporation of the Pearce algorithm (Pearce, 1977; 1980) into the depth phase identification procedure. In this approach, the relative amplitudes of P and any candidate pP and sP phases are determined for the various observing stations and processed by the Pearce algorithm to define the range of earthquake focal mechanisms which is consistent with these relative amplitude observations. This permits the relative amplitude characteristics of candidate depth phases to be assessed for consistency with the predictions for characteristic earthquake focal mechanisms in that source region, thereby greatly increasing the confidence in the depth phase identification. The investigation of improved confidence intervals on focal depth estimation determined from P-wave first arrival times has also continued, with Monte Carlo simulations being used to define precise confidence regions corresponding to generalized model assumptions. This model is currently being carefully evaluated using data from earthquakes for which the focal depths are well constrained by verified depth phase observations and is being extended to include the formulation of an hypothesis test which will be suitable for event screening purposes.

OBJECTIVES

The objectives of this research program are to determine more reliable estimates of the uncertainties associated with the different focal depth estimation procedures and to increase the number of events which can be identified as earthquakes on the basis of focal depth through the implementation of new and improved analysis tools. This is being accomplished through the development of improved procedures for identifying and using the teleseismic depth phases pP and sP, the incorporation of regional S-P based origin

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time constraints into an improved depth estimation algorithm and the development of more robust statistical hypothesis tests for use in event screening.

RESEARCH ACCOMPLISHMENTS

During the past year, work on this project has continued to focus on the development of improved tools for detection and identification of the depth phases pP and sP and on the continuation of the evaluation of a new algorithm for computing more reliable confidence intervals on focal depths determined from P wave first arrival times alone. With regard to depth phase identification, we have now completed an analysis of IMS data recorded from approximately 150 REB events located in the Hindu Kush, Hokkaido and central Honshu regions outlined in Figure 1. These data have been analyzed using a fully automated network stacking algorithm which employs signal analysis procedures similar to those originally proposed by Israelsson (1994) and more recently applied to a sample of Canadian data by Woodgold (1999). In this approach post-P arrivals observed at each station for a given event are mapped from functions of delay time to functions of source depth using the pP-P or sP-P delay times predicted by the IASPEI travel time tables for the various station distances. These functions of depth for all the stations in the detecting network are then added together to identify arrivals consistent with the predicted depth phase moveouts over the entire range of potential source depths. This transformation is illustrated in Figure 3, which shows the predicted pP moveout with respect to P as a function of source depth for two different epicentral distances. Using such predicted moveout curves, the observed delay times of all post-P arrivals with respect to P can be translated into equivalent focal depths under the hypotheses that they are either pP or sP arrivals. Those arrivals which are consistent with such hypotheses should then show up as peaks on the stacked network depth function. In the present application, difficulties associated with the variability of observed short-period signals between the widely separated IMS stations are avoided by stacking unit amplitude boxcar functions centered on the post-P detection times which are automatically determined at each station by the IDC front end signal processing procedures.

Some typical results of applying this network stacking algorithm to detection data from selected earthquakes in the Hindu Kush, Hokkaido and central Honshu regions are presented in Figures 3-5, respectively, where it can be seen that in each case there is a prominent peak near the corresponding REB depth which would be readily identified as a candidate pP depth phase. This procedure has now been systematically applied to all 150 REB events in our selected sample, and it has been found that prominent candidate pP and/or sP peaks can generally be identified in the resulting network stacks for a majority of these earthquakes, including some with mb values as low as 3.7 and depths as shallow as 50km. Thus, it appears that the proposed network stacking algorithm is effective at providing fully automated detection of candidate pP and sP arrivals at IMS network stations.

Of course, the automatic process described above only considers the consistency in timing of detections across the network and subsequent analyst review would be required to confirm the depth phase identification with high confidence. We have been investigating the feasibility of using the information inherent in the observed relative amplitudes of the various P arrivals at different stations to increase the confidence in the identification of such candidate depth phases. In this approach, the recorded short-period waveforms corresponding to the stations for which the automatic detections have been stacked are first presented to the analyst aligned on the time corresponding to the candidate depth phase peak under investigation. Such a display of the P wave data recorded from the Hindu Kush earthquake of 1995/08/17 is presented in Figure 6, where it can be seen that there are indeed some prominent arrivals at the predicted pP times corresponding to this candidate depth phase peak. Also shown on this figure are the annotated relative P and pP amplitude values which have been interactively estimated by an analyst. It has been shown by Bob Pearce of the IDC (Pearce, 1977; 1980) that such relative amplitude data can be systematically evaluated to identify the range of earthquake focal mechanisms which is theoretically consistent with the observations, and such information can potentially lead to greatly increased confidence in depth phase identification. That is, in principal, candidate depth phase amplitude data from an event under investigation can be used to define a range of permissible focal mechanisms consistent with these observations, and the compatibility of these focal mechanisms with the known regional tectonics can be assessed to further test the credibility of the proposed phase identification. One source of such regional

tectonic information is the historical Harvard centroid moment tensor (CMT) catalog, solutions from which are summarized for our selected Hindu Kush study area in Figure 7.

As an example of this validation process, the observed relative amplitude data from the Hindu Kush earthquake of Figure 6 have been processed using the RAMP code developed by Pearce (1980) to identify the range of permissible focal mechanism solutions which are theoretically consistent with these observed P/pP amplitude ratios. The resulting range of permissible solutions is graphically summarized in Figure 8 (left), where these solutions are compared with the range of focal mechanisms corresponding to the observed historical Harvard CMT solutions for the Hindu Kush region (right) from Figure 7. It can be seen that , in this case, a number of permissible solutions inferred from the phase amplitude rations for this event are consistent with historical CMT solutions for this region, which greatly increases the confidence of the identification of this candidate depth phase as pP.

With regard to focal depth estimates based on P wave first arrivals alone, we previously developed an approach to computing confidence intervals on focal depth that accounts for such complexities as nonlinearity of traveltime as a function of focal depth, uncertainty in the variance of arrival time picks, and errors in traveltime tables (“modeling errors”). Our approach defines a confidence interval as the set of focal depths that cannot be rejected at a given confidence level, using a likelihood ratio test statistic in the rejection test. To avoid linearity assumptions, Monte Carlo simulation is used to estimate the needed distribution of the test statistic. We are now extending our algorithm to perform a focal-depth discrimination test. For this test, the null hypothesis is that the focal depth is anywhere in the interval 0 to 10 km, in contrast to considering each individual depth as in the computation of confidence intervals. The test statistic is still taken to be a likelihood ratio, whose distribution is inferred by simulation. The result of the computation is the highest confidence level at which $0 < z < 10$ km can be rejected. If this level is sufficiently high (e.g., > 95%), a shallow focus can be rejected for the purposes of discrimination. We are currently applying our proposed focal depth discriminant to events in the northern and southern portions of our Hindu Kush study region, taking into account the uncertainty in the traveltime correction at station NIL.

CONCLUSIONS AND RECOMMENDATIONS

A research investigation directed toward the development of improved tools for detection and identification of the depth phases pP and sP and the evaluation of a new procedure for computing more reliable confidence intervals on focal depth estimates based on P wave first arrival times alone has now been largely completed. A principal result of this investigation has been the development and testing of a fully automatic algorithm for stacking raw IMS detection data to identify candidate depth phases for further review by the IDC analyst. This automatic algorithm has now been applied to data from about 150 REB events in the Hindu Kush, Hokkaido and Honshu regions. Prominent candidate pP and sP peaks have been identified in the resulting network detection stacks for a majority of these events, including some with m_b values as low as 3.7 and depths as shallow as 50 km. We conclude that this new automatic network stacking algorithm holds promise for providing a useful tool which could be used by IDC analysts to make more frequent and more reliable depth phase picks for use in event screening. Most recently, we have been extending this automatic procedure to permit the analyst to review any candidate depth phases and to assess their consistency with what is known about the regional tectonic environment in which the event occurred. In particular, the Pearce algorithm is being used to define the permissible range of focal mechanisms consistent with the relative amplitudes of P and any candidate pP and sP phases for a particular event, and these solutions are being compared with the range of observed focal mechanisms for that source region as represented by the historical Harvard CMT solutions. Initial tests of this evaluation procedure indicate that it can provide confirming evidence which could significantly increase the confidence in depth phase identification. It is our recommendation that these procedures be further refined and then tested in the IDC operational environment using the PIDC testbed. With regard to the determination of improved confidence intervals on depth, a more rigorous statistical method based on Monte Carlo simulation and grid search has now been implemented as is currently being evaluated using data recorded from Hindu Kush earthquakes with well-constrained focal depths.

Key Words: seismic, focal depth, discrimination, prototype International Data Centre, Hindu Kush

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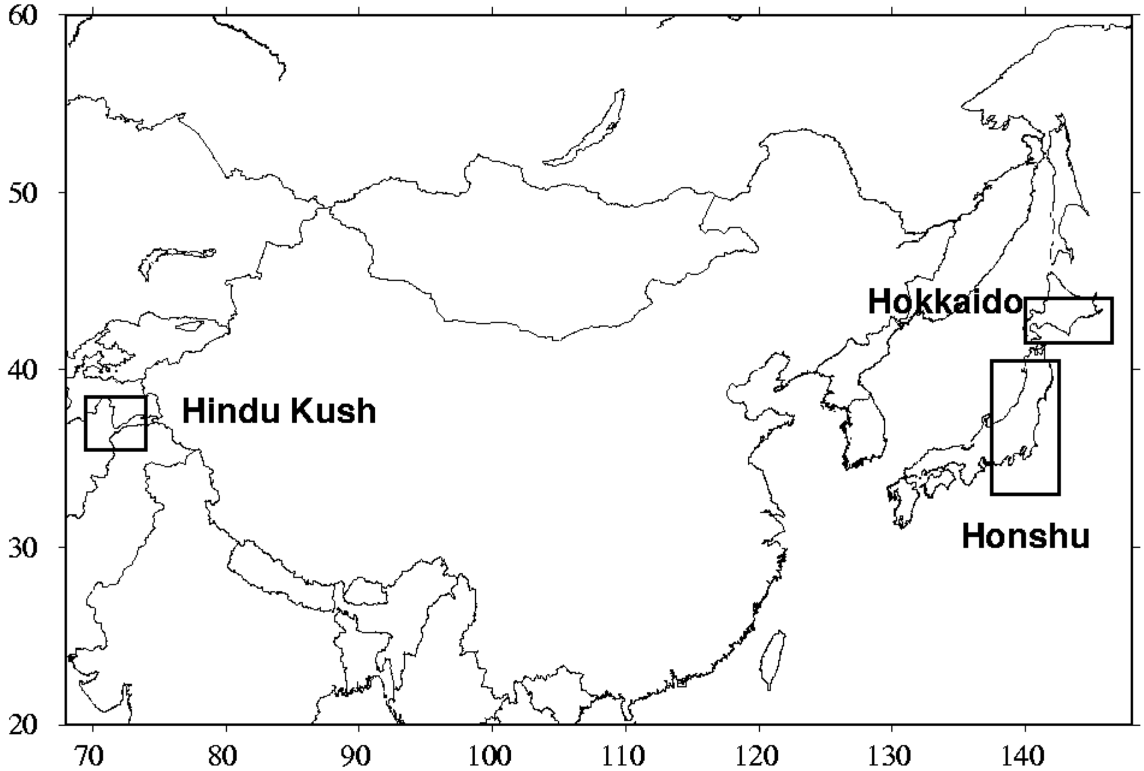

Figure 1. Map locations of the events in the Hindu Kush, Hokkaido and central Honshu regions used in the evaluation of the depth phase stacking algorithm.

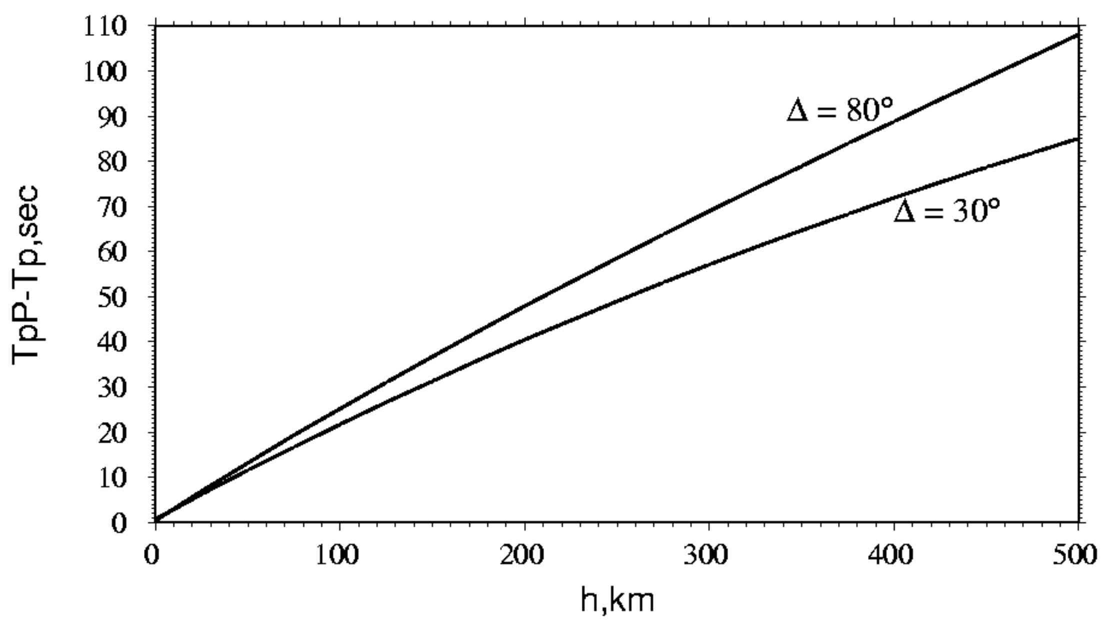

Figure 2. pP-P moveout times as a function of focal depth at fixed epicentral distances of of 30 and 80 degrees.

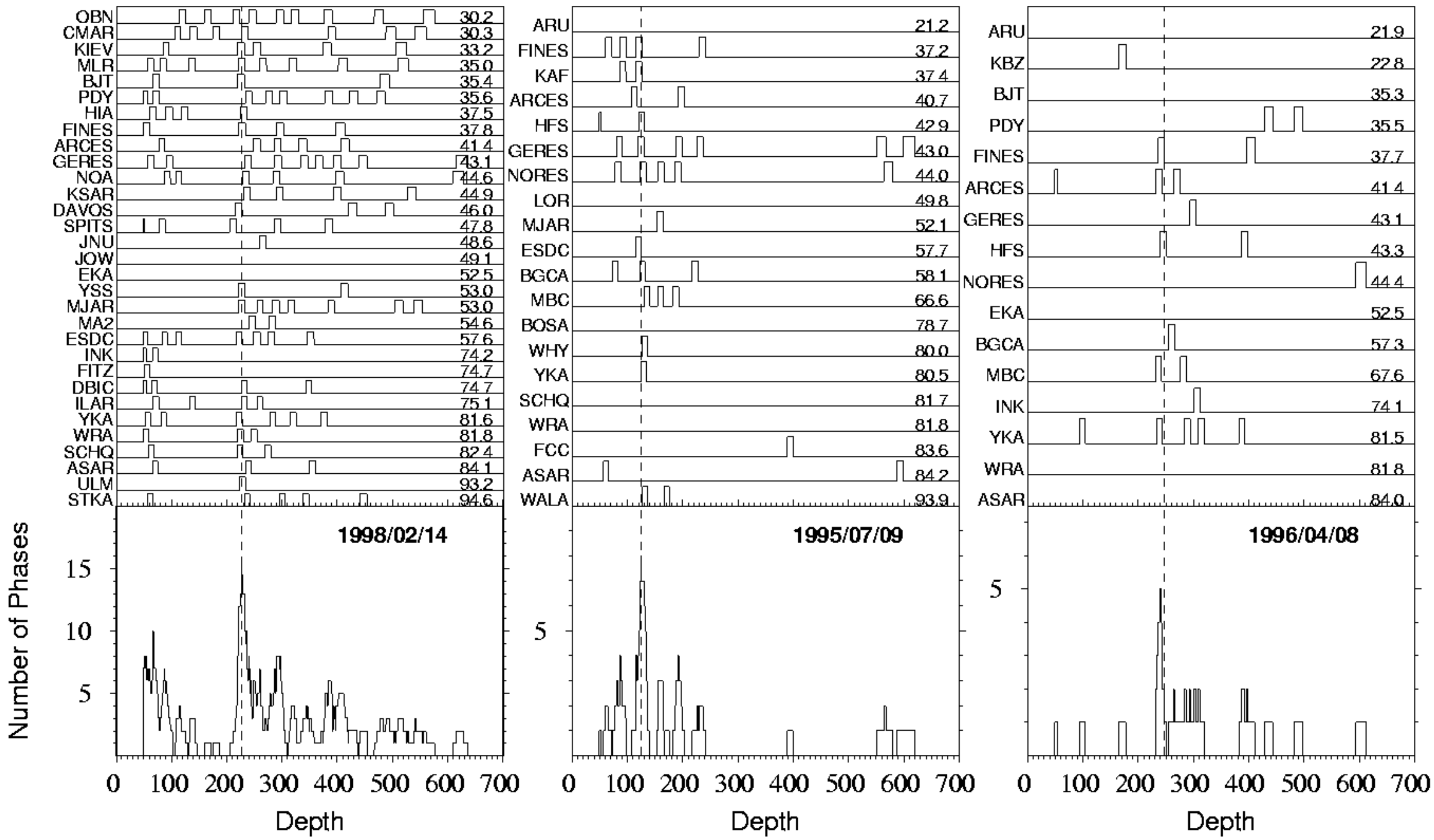

Figure 3. Network detection stacks of pP for the Hindu Kush earthquakes of 1998/02/14 ($m_b = 5.03$), 1995/07/09 ($m_b = 4.40$) and 1996/04/08 ($m_b = 4.04$). Note the prominent peaks near the corresponding REB depths which are indicated by the dashed vertical lines on these figures.

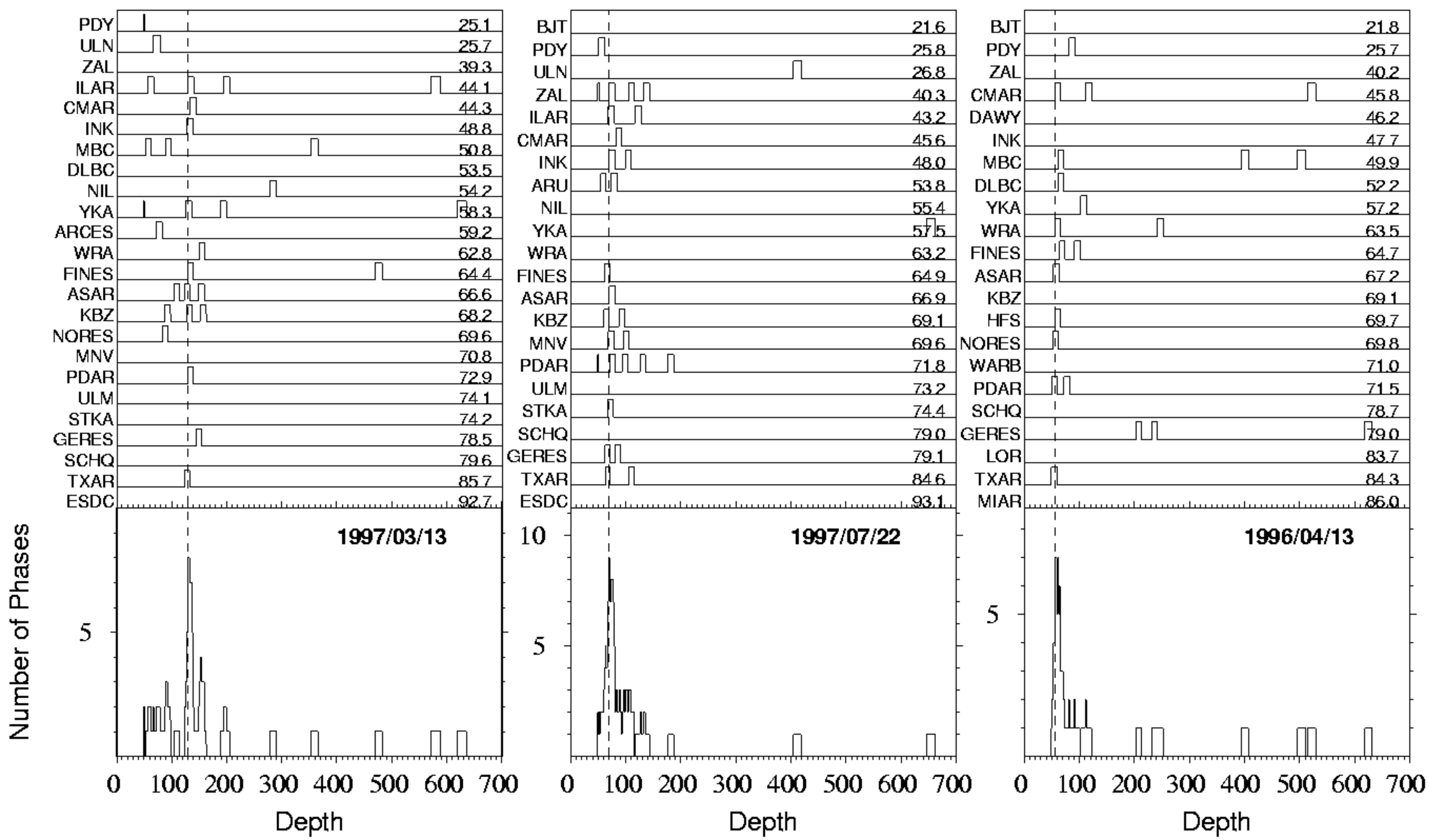

Figure 4. Network detection stacks of pP for the Hokkaido earthquakes of 1997/03/13 ($m_b = 4.34$), 1997/07/22 ($m_b = 3.97$) and 1996/04/13 ($m_b = 3.82$). Note the prominent peaks near the corresponding REB depths which are indicated by the dashed vertical lines on these figures.

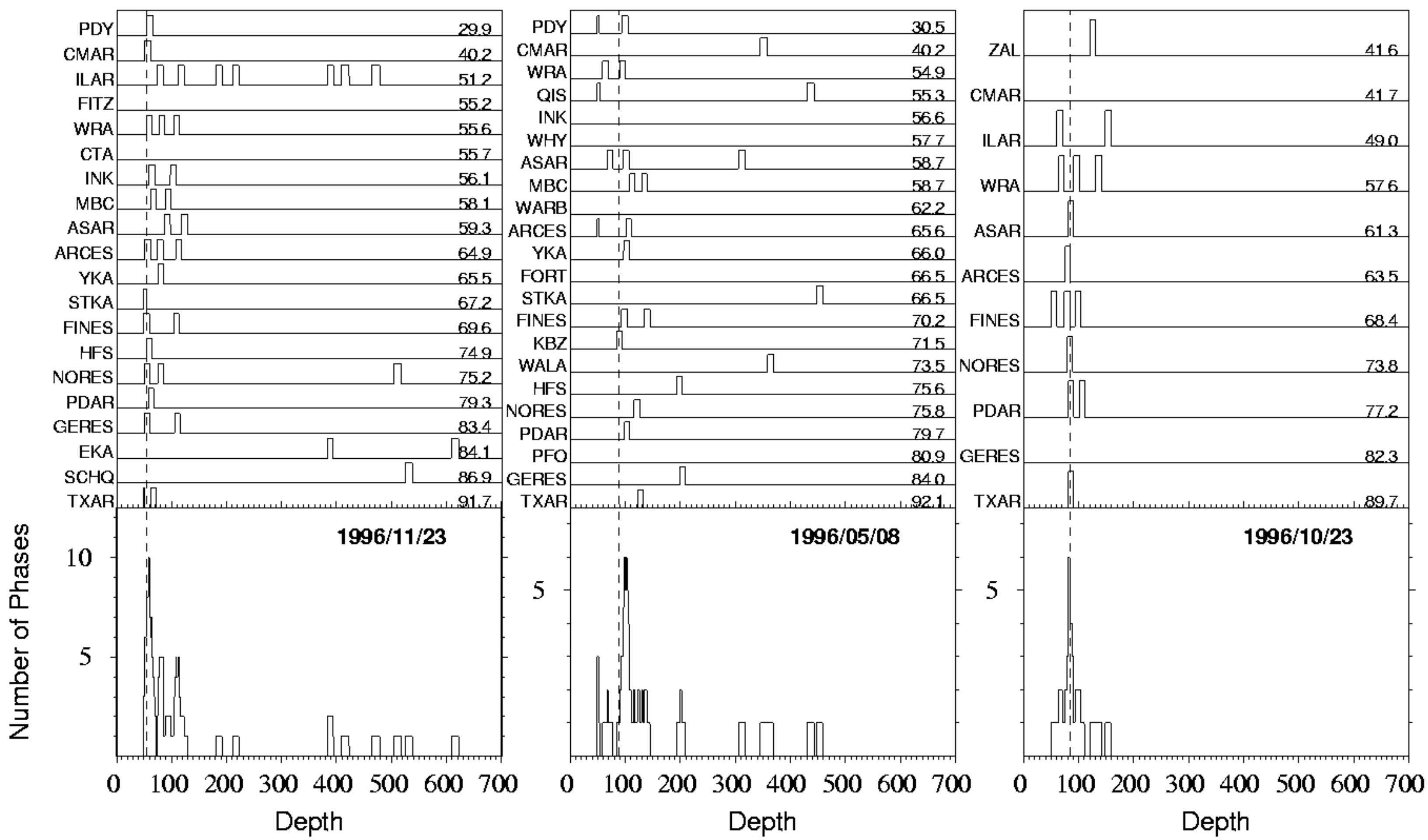

Figure 5. Network detection stacks of pP for the central Honshu earthquakes of 1996/11/23(m_b = 4.32), 1996/05/08 (m_b = 3.86) and 1996/10/23 (m_b = 3.79). Note the prominent peaks near the corresponding REB depths which are indicated by the dashed vertical lines on these figures.

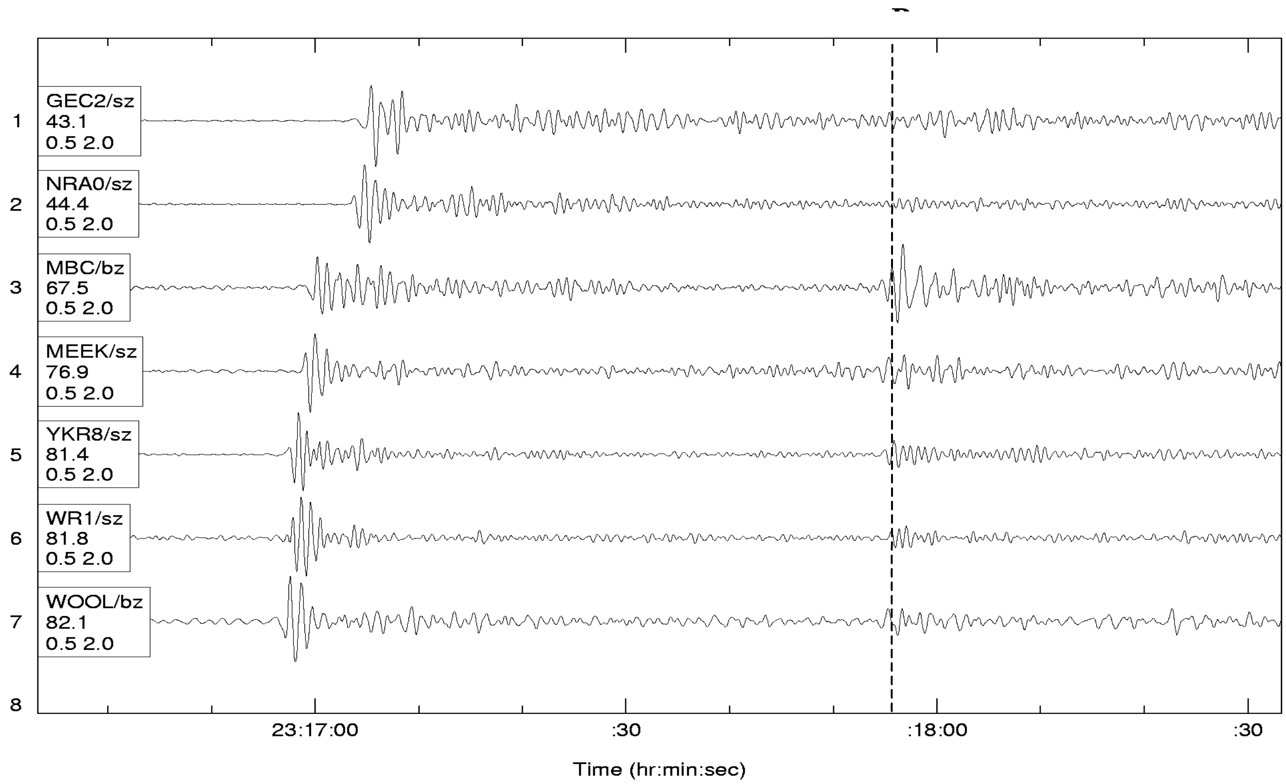

Figure 6. Vertical component teleseismic recordings of the Hindu Kush earthquake of 1995/08/17, shown aligned on the candidate pP phase arrival time identified by the network stacking algorithm. The annotated numerical values on each trace denote the relative amplitudes of P and pP to be used as input to the Pearce focal mechanism code RAMP.

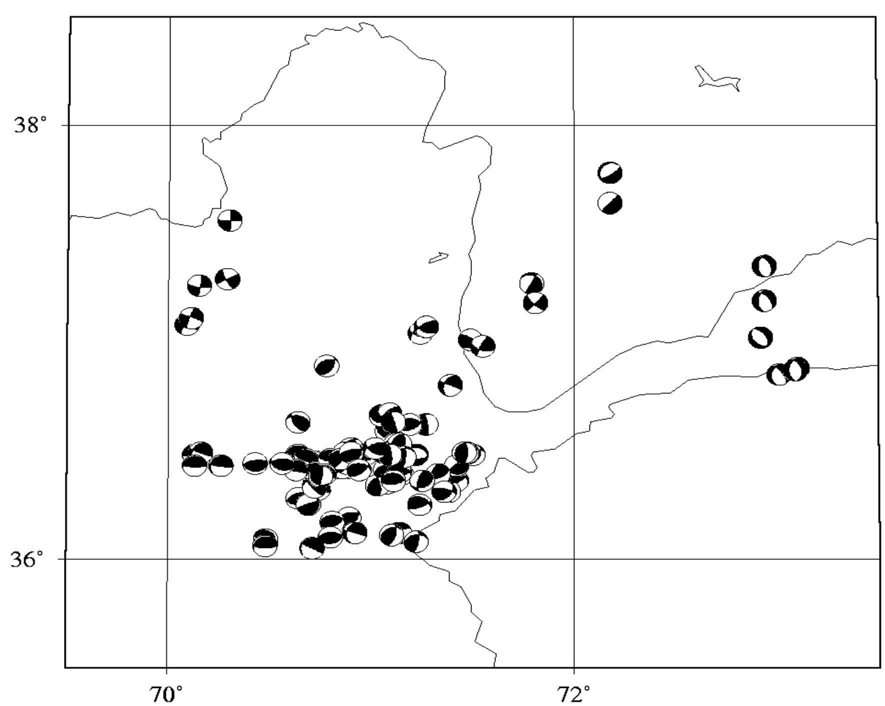

Figure 7. Harvard CMT focal mechanism solutions for historical earthquakes in the Hindu Kush region.

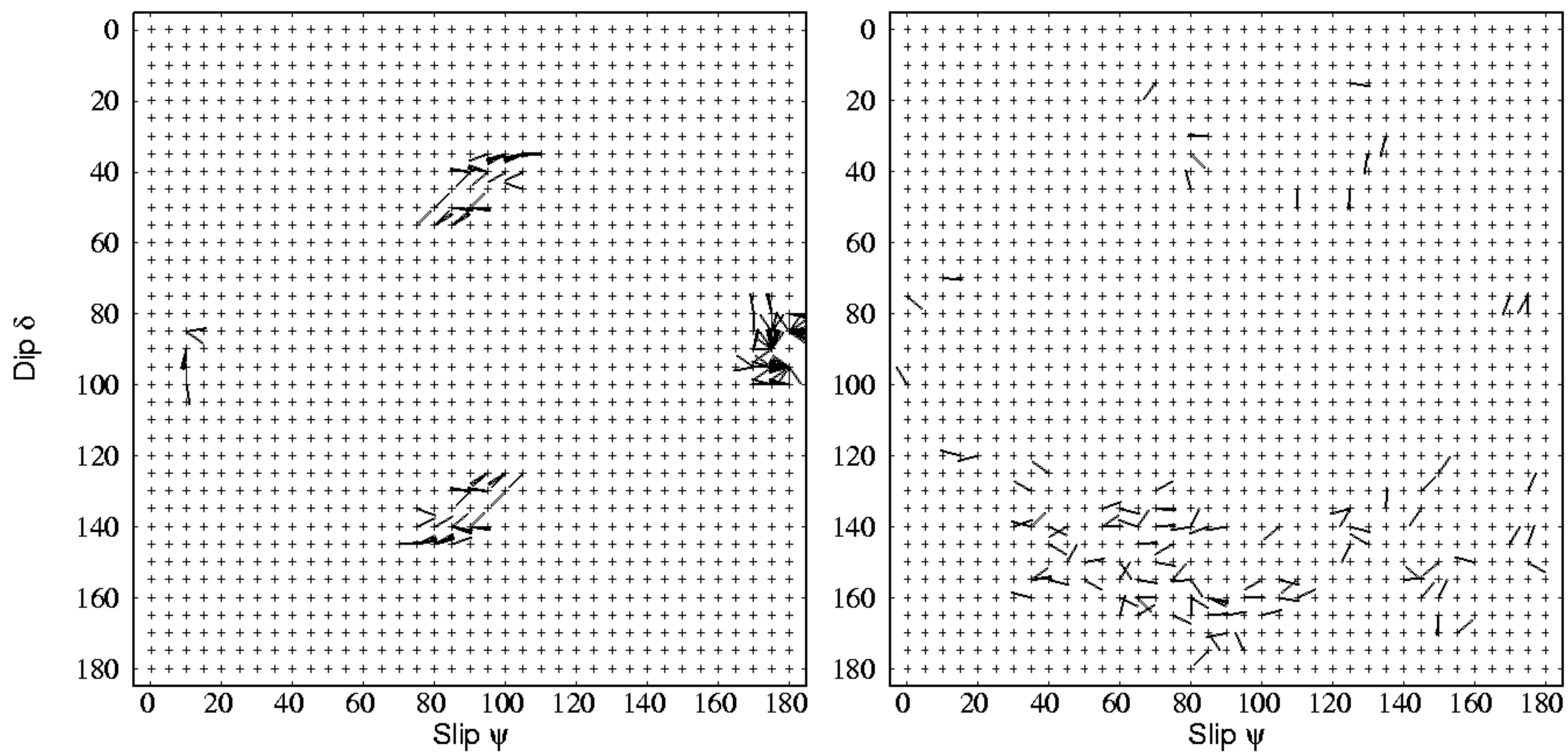

Figure 8. Comparison of permissible focal mechanism solutions for the Hindu Kush earthquake of 1995/08/17 determined by the RAMP code from the observed P/pP amplitude ratios (left) with the historical Harvard CMT solutions for earthquakes in this region (right). The orientations of the line segments representing the individual solutions indicate the strikes of the focal mechanisms, measured clockwise from north.